Nitric Oxide Emission Studies of Internal Combustion Engines

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This article reports on the methods and results of preliminary experiments that have been conducted with an ASME–CFR (American Society of Mechanical Engineers–Committee on Fuel Research) engine in order to determine the effect of fuel composition on the emission characteristics of an internal combustion engine. Initial emphasis was placed upon a comparison of the nitric oxide emissions within the exhaust for various mixtures of natural gas and gasoline. A pneumatically driven atomizer permitted the CFR engine to be operated with gasoline fuel–air ratios down to 0.05. At fuel–air ratios below 0.05, misfiring occurred when either natural gas or gasoline fuels were used. In a natural gas–gasoline fuel mixture, the nitric oxide concentration in the emissions decreased almost linearly with increasing concentration of natural gas, based on a fuel–air ratio near 0.063. It is shown, for the limited conditions investigated, that the concentration of NO_x in the exhaust (on the basis of mass discharged for unit work done) is always less when natural gas is the fuel, except for a limited range of operation at very lean equivalence ratios where misfiring precluded a direct comparison. However, the emissions were never reduced by more than ½, and were limited to approximately 20% over a substantial part of the equivalence ratio range ($1.0 < 0 < 1.3$).

Introduction

The development of a low pollution engine for automotive applications that will meet or surpass the 1975–1980 standards set forth in the California Pure Air Act of 1968 (AB 357) is fraught with compromise. Proposals varying from minor modification of the internal combustion engine, including add-on devices for exhaust gas treatment, to outright substitution with, for example, external combustors (fossil-fueled steam engines) or electric cars (ultimately based on nuclear reactors as an

energy source) are many and varied. Although the latter approach may ultimately be implemented, it seems clear that the current national investment in the internal combustion engine and the substantial half-life (3 to 5 yr, assuming 100% changeover for all new units starting at some arbitrary time) of this system dictates a near-term solution based on the former approach. Thus, it is essential that the potential improvements that are available with minor engine modifications (preferably suitable for retrofit to existing vehicles) and/or fuel composition be thoroughly evaluated. It was to this end that a series of experiments were initiated as a part of the activity of the "Low Pollution Vehicle Study Group," which includes JPL staff and California Institute of Technology (Caltech) faculty. The bulk of the experimental work is being carried out by Caltech students.

In view of the recent interest in the use of natural gas (NG) as a substitute for gasoline, the first set of experiments was devised to compare emission characteristics from a given engine when run alternately on gasoline and natural gas. Previous results have demonstrated substantial improvements for multicylinder engines where manifolding (1) introduces severe complications for liquid-fueled systems (based on normally aspirated carburetors), and (2) enhances mixing for gaseous-fueled systems. These results may be more representative of manifolding effects than "composition"; hence, an investigation to determine whether or not composition *per se* would materially alter emission characteristics was initiated.

The results reported here are concerned only with the formation of NO_x as a function of inlet fuel composition for a given set of engine operating conditions. Analogous measurements of CO, CO_2, and unburned hydrocarbons were also obtained but these results are not included in this report.

These initial experiments have shown that mixtures of natural gas and gasoline do not produce a significant synergistic effect and that replacing gasoline with natural gas results in reductions in *peak* levels of about 24% in terms of NO_x in grams per kilowatt-second (g/kW-s) (see discussion of results for this extrapolation). However, the reduction in available power is substantial. Further, it is shown that with *well-atomized* gasoline, it would be possible to control mixture ratio so as to achieve even lower NO_x emissions at greater efficiencies with gasoline than with natural gas.

It should be emphasized that these results in themselves cannot preclude the desirability of utilizing natural gas in internal combustion engines. As noted above, the emissions of NO_x *are* reduced, and it can be argued that the compromises associated with reduced power output can be offset by reductions in hydrocarbon reactivity index for emissions from natural gas combustion. Any particular conversion must also con-

sider such factors as economy of operation, availability of natural resources, and fuel supply and distribution.

It is noted that these observations are for a limited set of operating conditions and are therefore restricted by those limits.

Experimental Methods

The experiments reported here were conducted with an ASTM–CFR (American Society of Mechanical Engineers–Committee on Fuel Research) single cylinder engine running throttleless (full throttle) at a constant 900 rev/min. The engine was motored except when brake-horsepower measurements were being made. Initial testing was done with a compression ratio of 7 and with a constant spark advance of 10 deg.

The original variable float level carburetor was replaced by a fuel injection system to allow the blending of air, natural gas, and gasoline. To this end the induction system was modified to incorporate a pneumatically driven liquid atomizer of conventional design (Spraying Systems Company Model No. 1A). The atomizer was operated so as to assure a mean drop size less than 20 μm[1] and to yield a mixture that would behave essentially like a gas. In addition it was mounted in a tube bolted directly to the inlet flange of the engine so that liquid deposition on walls was minimized.

Provisions were made to vary the composition of the fuel from 100% gasoline to 100% natural gas in an attempt to (1) evaluate the potential of the so-called mixed or dual systems that are being proposed (Reference 1), and (2) determine whether or not adding small amounts of natural gas to gasoline could yield disproportionate benefits for a fuel comprised of a mixture of natural gas and gasoline. For these latter experiments the working fluid for the pneumatic atomizer became a mixture of natural gas and compressed air (infinitely variable from 0 to 100% natural gas) so that the atomization characteristics of the gasoline were maintained nearly constant. Thus, in summary, the induction system provided a common source for the injected fuel which could be composed of any ratio of natural gas/gasoline at any desired fuel–air ratio. The system will also be utilized in future experiments to evaluate the effects of mean drop size *per se* on combustion and emission characteristics.

Fischer–Porter rotameters were used to monitor the mass flow rates. A disc brake torquemeter was installed to allow measurement of the output power developed by the engine. A mixing tank (with a volume equal to approximately 35 cylinder volumes) was installed in the exhaust line to eliminate problems of concentration stratification.

[1]Presumed from manufacturer's specifications alone; not proven.

On-line analysis of the exhaust products was achieved with a high-speed, quadrapole, mass spectrometer (E.A.I. Quad 300) monitoring the effluent from a sampling probe installed downstream of the mixing tank. This system was used to measure, with relative precision, the concentrations of NO, CO, CO_2, CH_4, and C_2H_6.

In order to aid in the measurements of the higher hydrocarbon emissions, a Carle Model 9000 gas chromatograph (with a flame ionization detector) was also arranged so as to permit on-line sampling of the exhaust. The electrical signals from the gas chromatograph were: (1) integrated by means of an Infotronics Model CRS-100 digital integrator, and (2) displayed on a Hewlett-Packard Model 7127A strip chart recorder. This system is providing excellent data on hydrocarbon emissions, but, as indicated previously, this information is not included in this report.

As shown in Figure 1 a control panel is used to control and monitor flow rates of air and fuels flowing to the CFR engine; the disc brake and the on-line mass spectrometer are in the background, whereas the on-line gas chromatograph system (although present) is not visible in the picture.

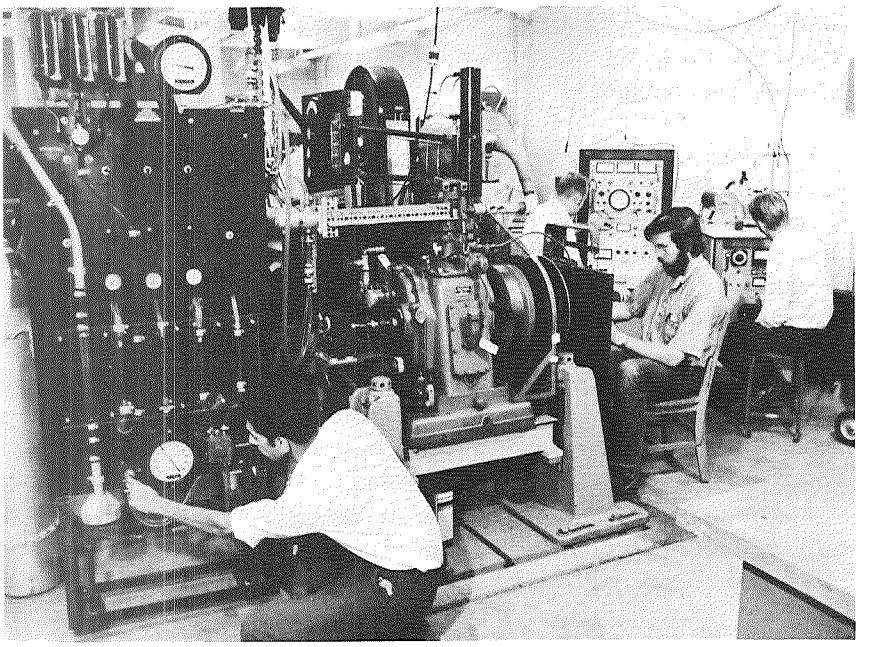

Figure 1. CFR engine and instrumentation for determining exhaust emissions

Experimental Results

The concentration of NO_x in the exhaust versus fuel–air ratio for this engine is shown in Figure 2; the curve with a maximum at approximately

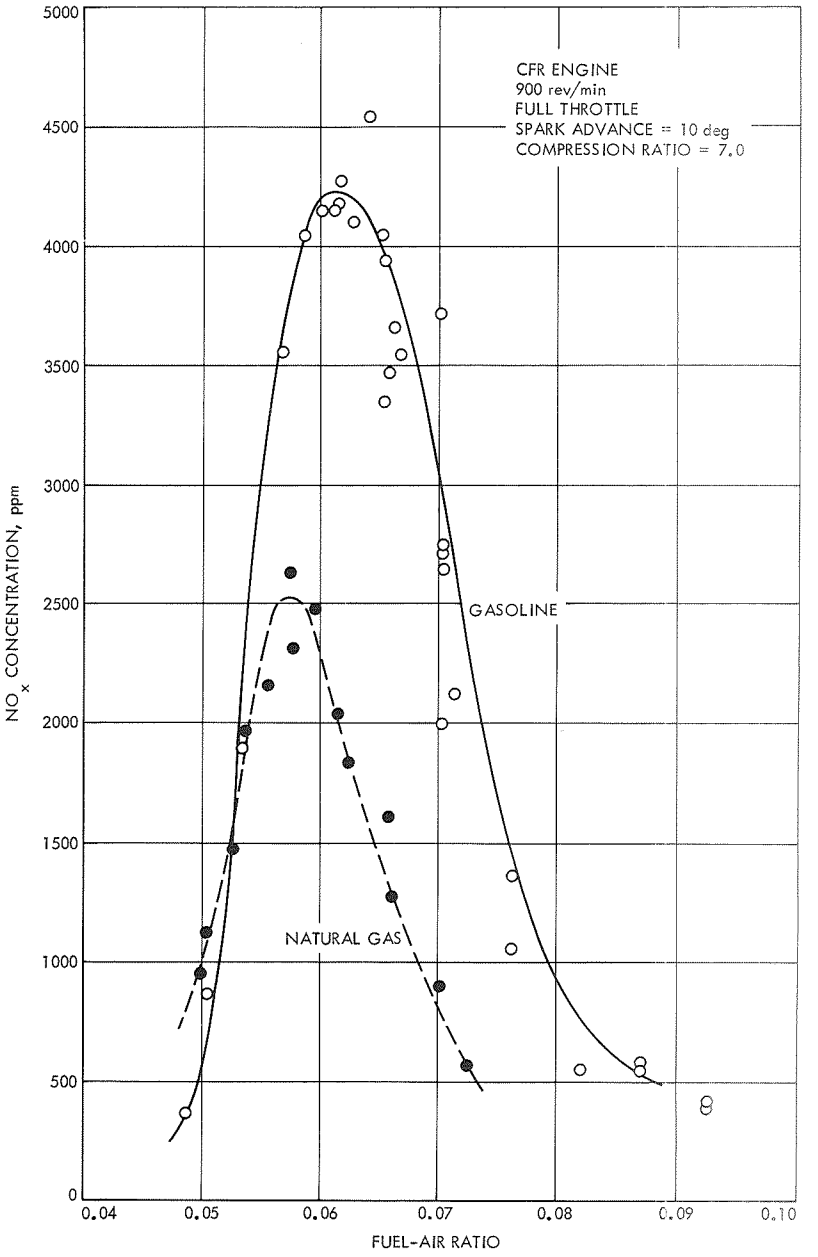

Figure 2. NO_x concentration in exhaust of an internal combustion engine burning natural gas or gasoline

4200 ppm is that obtained for several gasolines purchased at random from local outlets, whereas the other curve is for natural gas, nominally composed of 90% CH_4 + 9% C_2H_6 + residual CH + H_2. The stoichiometric fuel–air ratio for these gasolines is near 0.0645 and for natural gas is 0.0578. Where there is overlap, there is good agreement between

these results and those reported previously (for example, see Figure 4 of Reference 2).

Figure 3 indicates how the concentration of NO_x varies with the percent of natural gas in the fuel. These data are being analyzed with respect to theoretical models put forth by Newhall (Reference 3) and by Lavoie, Heywood, and Keck (Reference 4). Tests are planned to determine the comparable lean limit equivalence ratio associated with the original CFR carburetor system.

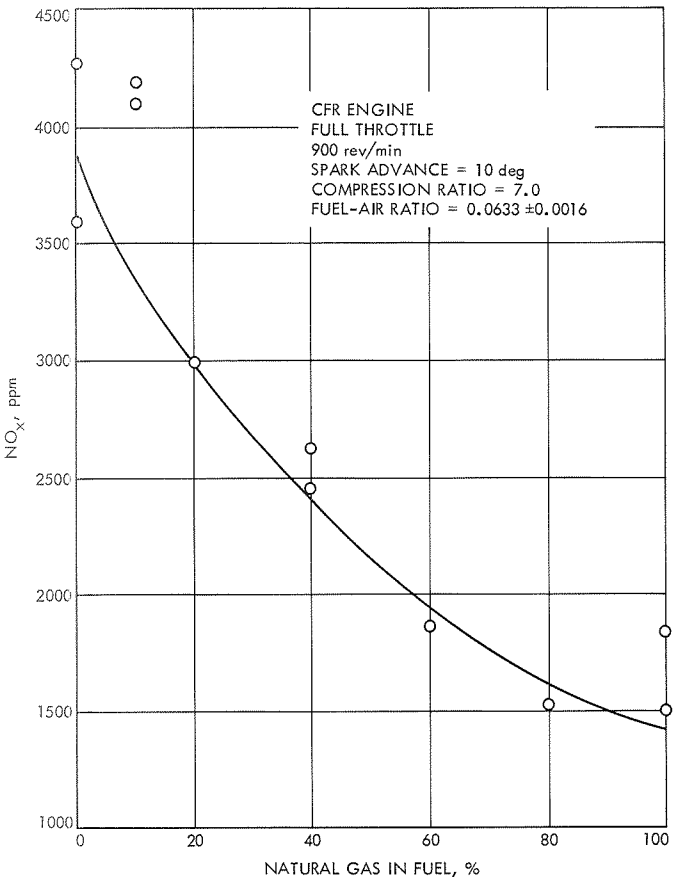

Figure 3. NO_x concentration in exhaust of an internal combustion engine burning mixtures of gasoline and natural gas

A comparison of engine performance, in terms of brake horsepower and specific fuel consumption versus fuel–air ratio, for natural gas and gasoline is presented in Figure 4. Clearly, the characteristic reduction in horsepower and the associated increase in specific fuel consumption (which is partially offset by the increase in heat of combustion) when burning natural gas are not negligible. Therefore, a proper comparison

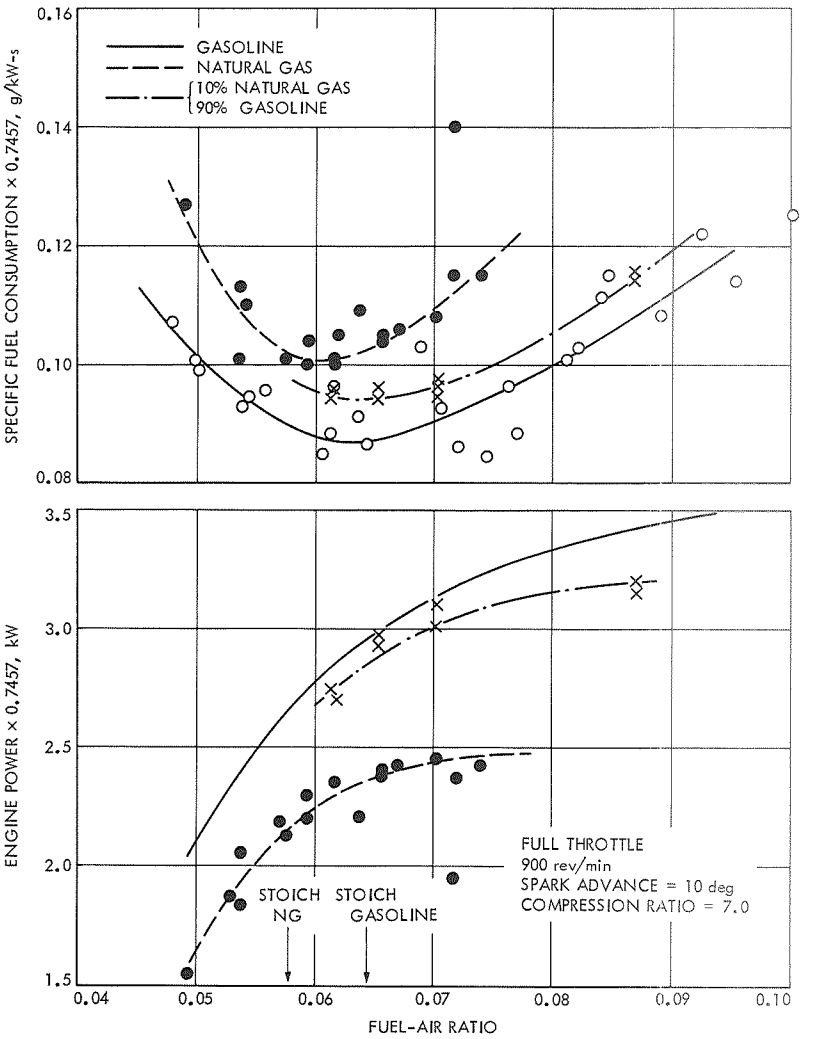

Figure 4. CFR engine performance with gasoline and natural gas

of the emission characteristics of these two fuels should incorporate the effects of this compromise.

It should be emphasized that Figures 2 and 3 deal exclusively with NO_x formation; other data are being reduced wherein consideration is given to the photochemical reactivity associated with the hydrocarbon product distribution.

Discussion of Results

When these data are presented as in Figure 2, it is observed that: (1) gasoline produces substantially greater quantities of NO_x than does natural gas for fuel–air ratios greater than about 0.057; (2) for fuel–air

ratios leaner than about 0.057, the emission levels for these two fuels are similar; and (3) for fuel–air ratios less than about 0.053, gasoline actually produces lower emission levels than does natural gas. Thus, it can be argued that emission levels for natural gas are similar to gasoline for lean fuel–air ratios but substantial reductions in NO_x formation are available for fuel-rich operation—even though, as illustrated in Figure 4, the compromises in terms of fuel economy (cost) and horsepower (engine size) are costlier for fuel-rich operation. It follows, then, that with well-atomized gasoline, the benefits to be derived by substituting natural gas for gasoline as an automotive fuel must stem from operation in the fuel-rich condition, not the lean condition, as is commonly stated.

It is of interest to point out that these conclusions must be modified somewhat if the comparison is based on the equivalence ratio rather than the fuel–air ratio. Thus, when the concentration data of Figure 2 are converted to an emissions rate, in terms of NO_x in grams per hour (g/h), and the comparison of emissions and engine performance portrayed as a function of fuel equivalence ratio[2] (as illustrated in Figures 5 and 6), it can be seen that the emission levels for natural gas always fall below those for gasoline. Further, substitution of natural gas for gasoline produces a nearly constant 28–30% reduction in available horsepower over the entire range of equivalence ratios, and the compromise associated with fuel economy is no longer so mixture ratio dependent—except that it is "desirable" to operate at or near equivalence ratio unity where the penalty, in terms of increased specific fuel consumption, for converting to natural gas is limited to approximately 14%.

It is interesting to note that, on an equivalence ratio basis, the lean stability limit for the "well-atomized" gasoline system is even lower than that for natural gas. Hence, the potential for controlling emissions by operation with "Lean air–fuel mixture carburetion . . . achievable by means of air–fuel mixture homogenation," as concluded by Kopa (cf Reference 5), is also demonstrated in these experiments with the CFR engine. Note that a similar conclusion is not strictly true when natural gas is the fuel. As seen in Figure 5, substantial amounts of NO_x are still being produced at the lean stability limit and it follows therefore that the only way to reduce these emissions further is to operate in the relatively rich region where the fuel–air equivalence ratios exceed approximately 1.18.

If the data of Figures 5 and 6 are combined to reflect the emission rate in terms of the work done, as shown in Figure 7, then the relative advantages associated with substitution of natural gas for gasoline are further reduced. It can be seen that if the comparison is made at their respective maxima, natural gas produces approximately 76% as much

[2]Fuel equivalence ratio ϕ is equal to the fuel–air ratio divided by the stoichiometric fuel–air ratio.

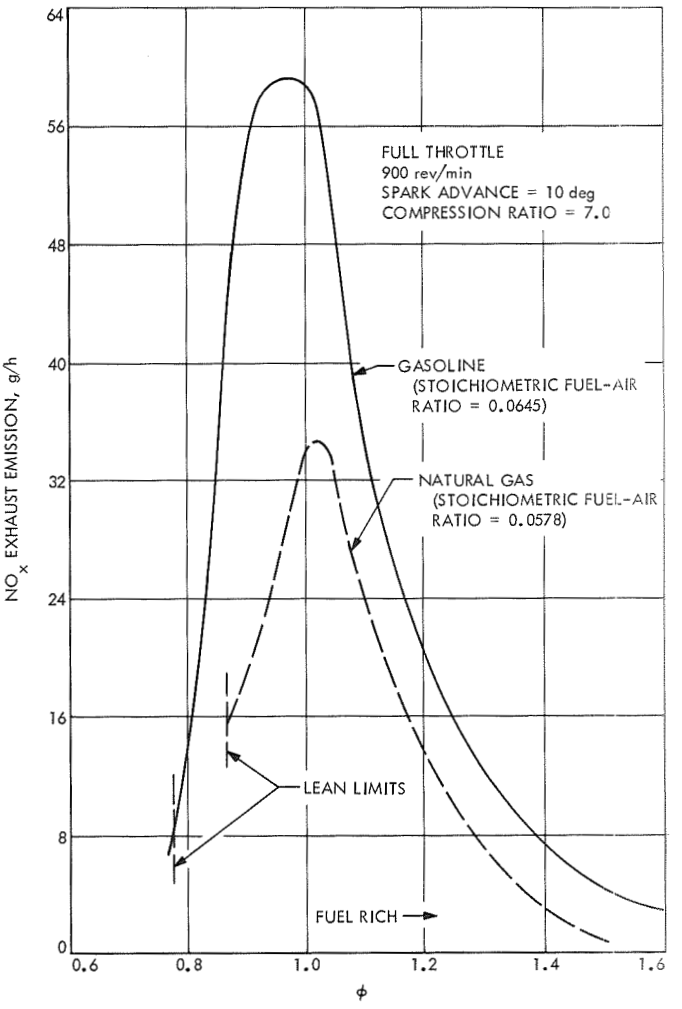

Figure 5. NO_x emission from CFR engine for two fuels

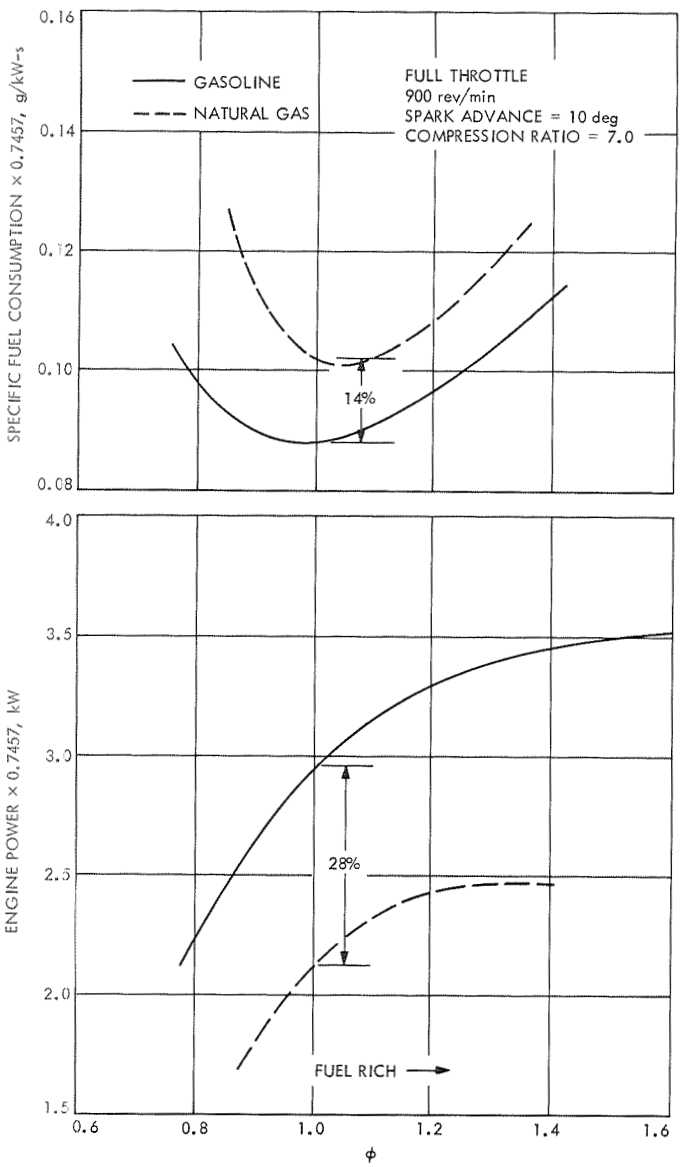

Figure 6. CFR engine performance as a function of fuel equivalence ratio with gasoline and natural gas

NO_x as does gasoline. However, this ratio rises to approximately 90% over most of the fuel-rich region.

The "relative" emission rates for the two fuels is illustrated in Figure 8, where it can be seen that gasoline always produces more NO_x. However, the difference is only about 8% at the minimum and does not exceed 20% for a rather broad range of equivalence ratios. Further, the data do not allow a comparison at the lean limit where the ratio would

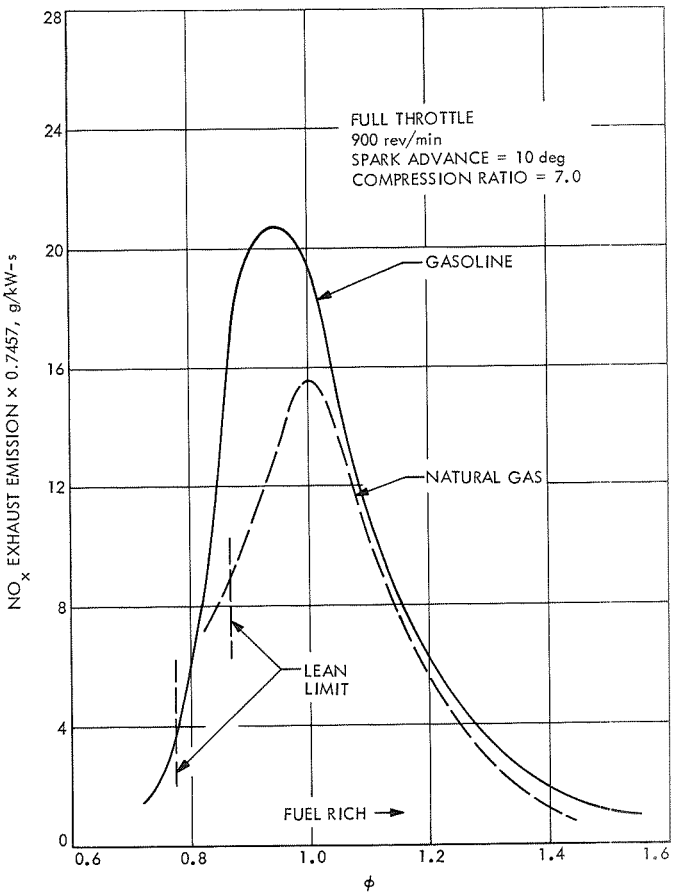

Figure 7. NO_x emission as a function of fuel equivalence ratio from CFR engine for two fuels

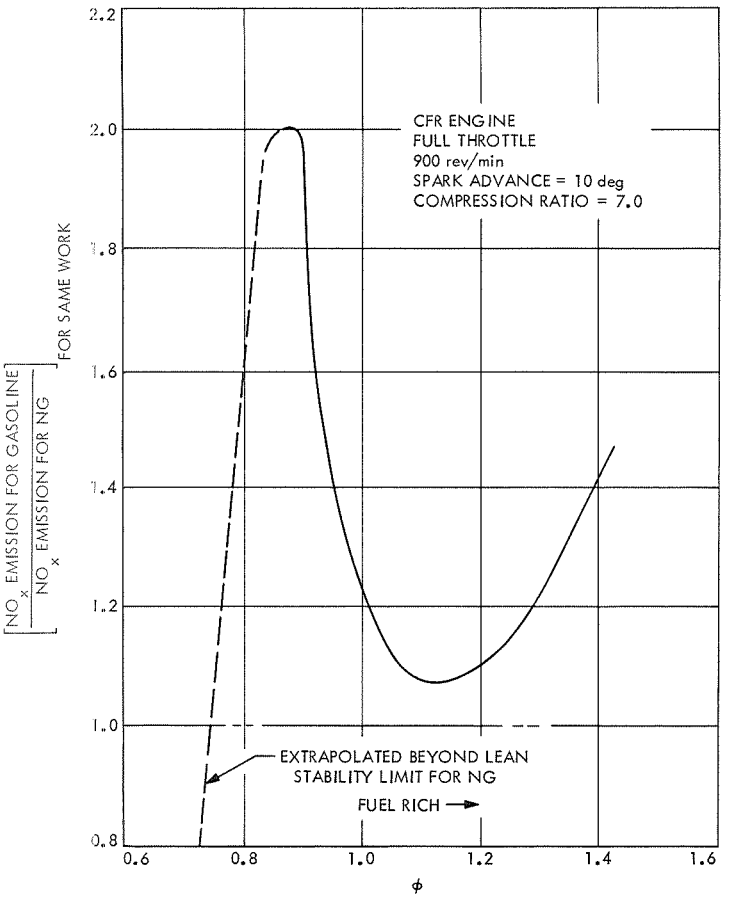

Figure 8. **Relative NO_x emission for gasoline and natural gas fuels doing same work**

(apparently) be less than 1.0. One should also note that in the fuel-rich regions the absolute emission levels are small for both fuels (see Figure 7).

Conclusions

Preliminary results of this study have shown that:

(1) The substitution of natural gas for gasoline as the fuel for an internal combustion engine:

(a) Yields fractional reductions in peak NO_x emissions for a given amount of work done.

(b) Compromises available horsepower by about 28%.

(c) Imposes a requirement that the engine be run rich (not lean) in order to minimize NO_x.

(2) The lean stability limit equivalence ratio for gasoline is less than that for natural gas if an efficient atomizer is utilized.

(3) The figure-of-merit for any pollutant cure must reflect the useful work done.

(4) Mixtures of natural gas and gasoline do not produce any appreciable synergistic effect insofar as reduction of NO_x is concerned.

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